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Heat Transfer Surface Enhancement through the Use of Longitudinal Vortices: A Review of Recent Progress

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■ Flow through an interrupted or enhanced heat exchanger passage is complicated and may cause the natural formation of vortices that can enhance local heat transfer by several hundred percent. Vortex-induced heat transfer enhancement exploits this effect through the deliberate generation of large-scale longitudinal vortices in the flow. In this review of vortex-induced heat transfer enhancement, the theoretical basis for the method is discussed and both active and passive implementations are reviewed. The aim of this survey is to critically review recent progress and to identify research needs in the area of vortex-induced heat exchanger enhancement.

Keywords: *heat transfer enhancement, pressure drop, longitudinal vortices, delta winglets, heat exchangers*

INTRODUCTION

There are many applications where the effectiveness of fluid-to-gas heat exchangers is important to the thermal performance of a process or system. Numerous examples may be found in heating and air conditioning, refrigeration, transportation, petrochemical and food processing, and other industries. Heat exchanger performance is often limited by the gas side because transfer coefficients are inherently lower for the gas side than for liquid or two-phase flow. This limitation and the desire to improve energy performance with reduced volume and manufacturing costs continues to motivate research in gas-side heat transfer enhancement. In this article, we present a review of recent progress in vortex-induced air-side heat transfer enhancement.

Single-phase heat transfer enhancement methods may be classified as active, passive, or compound [1]. Active methods require external power, such as electric or acoustic fields, mechanical devices, or surface vibration, whereas passive methods do not require external power but make use of a special surface geometry or fluid additive. Enhancements that simultaneously use more than one method are referred to as compound methods. Further classifications are possible and may be helpful in describing the underlying physics of an enhancement method.

The air-side temperature distribution is intimately coupled to the velocity field, often taking the form of a thermal boundary layer. This temperature distribution is a manifestation of the air-side heat transfer resistance, and it can be modified through flow manipulation. There are two methods of flow manipulation: alterations to the main flow and the introduction or exploitation of secondary flows. Two alternative classifications for heat transfer enhancement thus emerge: main-flow enhancement and secondary flow enhancement. In main-flow enhancement, the gross characteristics of the flow are altered through geometric changes, pressure variations, or by other means. In secondary flow enhancement, local flow structures are deliberately introduced. In some cases, it may be difficult to distinguish between main-flow and secondary flow methods, and in some cases they may be coupled. The main flow can be actively or passively altered. Wavy fins and furrowed channels are examples of passive main-flow enhancement methods; so are louvers and strip fins. Flow pulsation is an active main-flow method. Secondary flow enhancement can also be active or passive. The use of surface protuberances is a passive secondary flow method, and using electrohydrodynamics (EHD) to generate a localized "corona wind" is an active secondary flow enhancement.

In a heat exchanger, vortices, such as the horseshoe vortex illustrated in Fig. 1*a*, occur naturally in the flow. The intentional generation of vortices to enhance heat transfer (see Figs. 1*b* and 1*c*) is a secondary flow enhance-

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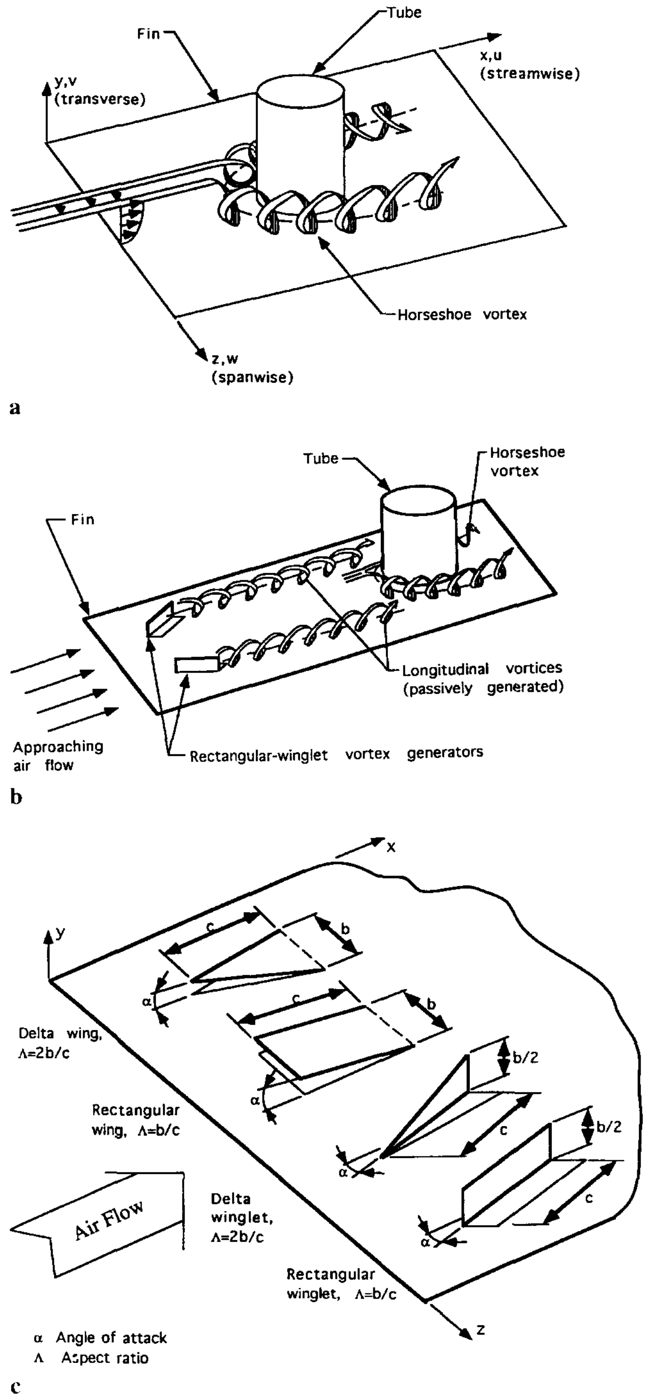

Figure 1. Natural and passively generated vortices and vortex generators for heat exchanger applications. (*a*) The natural formation of a laminar horseshoe vortex at a fin–tube junction: (*b*) typical passively generated longitudinal vortices; (*c*) common vortex generators and the associated geometrical definitions.

ment method; vortex-induced air-side heat transfer enhancement may be actively or passively implemented. In this review, we first discuss the origins of the method and its physical basis, then present a critical review of passive vortex methods, and finally briefly consider active methods. Our purpose is to critically review recent progress in the field and to identify areas where further research is needed.

BACKGROUND

A review of the early use of streamwise vortices in boundary layer control was presented in 1960 by Schubauer and Spangenberg [2], who also measured the effects of a number of mixing and vortex-generating surface elements on boundary layer development. Early research in this area was focused on the application of streamwise vortices to delay boundary layer separation on aircraft wings.

To our knowledge, the first archival article on the heat transfer impact of vortex generators appeared in 1969 [3]. The authors, Johnson and Joubert, studied a right circular cylinder in cross flow with delta winglet vortex generators located at a fixed angular position on the cylinder. Vortex generators increased the measured local Nusselt numbers as much as 200%, but overall heat transfer results were not encouraging because of decreases elsewhere on the cylinder. Local enhancements were explained in terms of enhanced thermal mixing, and the areas of reduced heat transfer were explained through the diminished impact of recirculation eddies behind the cylinder.

An early study that more clearly elucidated the mechanisms of local enhancement was reported by Kataoka et al. [4]. They addressed the local behavior for an inner rotating cylinder and an outer stationary cylinder with an imposed axial velocity in the annulus. This arrangement results in a system of axially advected Taylor vortices. Measurements obtained through a chemical mass transfer method indicated that heat transfer was locally enhanced in the region where two neighboring vortices induced a flow toward the heat transfer surface (downwash region). Conversely, in regions where neighboring vortices induced an outflow (i.e., in an upwash region) a decrease in local heat transfer was measured. While this situation differs from a boundary layer flow, the results generally indicate that local thinning of the thermal boundary layer associated with the secondary flow is responsible for the heat transfer enhancement. This description of the physics, illustrated in Fig. 2 for a flat plate, also provides some insight into why the heat transfer and pressure drop effects of longitudinal vortices are not simply related: the pressure drop associated with wall friction is related to the derivative of the streamwise velocity (the spanwise and normal velocities have little direct effect), but the spanwise and normal velocities play a significant direct role in convective heat transfer. Notwithstanding this complication, the analogies between momentum, energy, and mass transfer apply, and these analogies (e.g., Reynolds and Chilton–Colburn) may be exploited as discussed later.

Streamwise vortices may also occur when a flow suddenly encounters a surface element protruding into the boundary layer, as shown in Fig. 3. Sedney [5] presented a thorough review of the effects of small protuberances on boundary layer flows. For laminar and turbulent boundary layers, the effects of a three-dimensional surface bump are qualitatively similar. A system of vortices forms near the protuberance, bending around the disturbance to be carried downstream in a horseshoe pattern. This secondary flow depends very little on the shape of the protu-

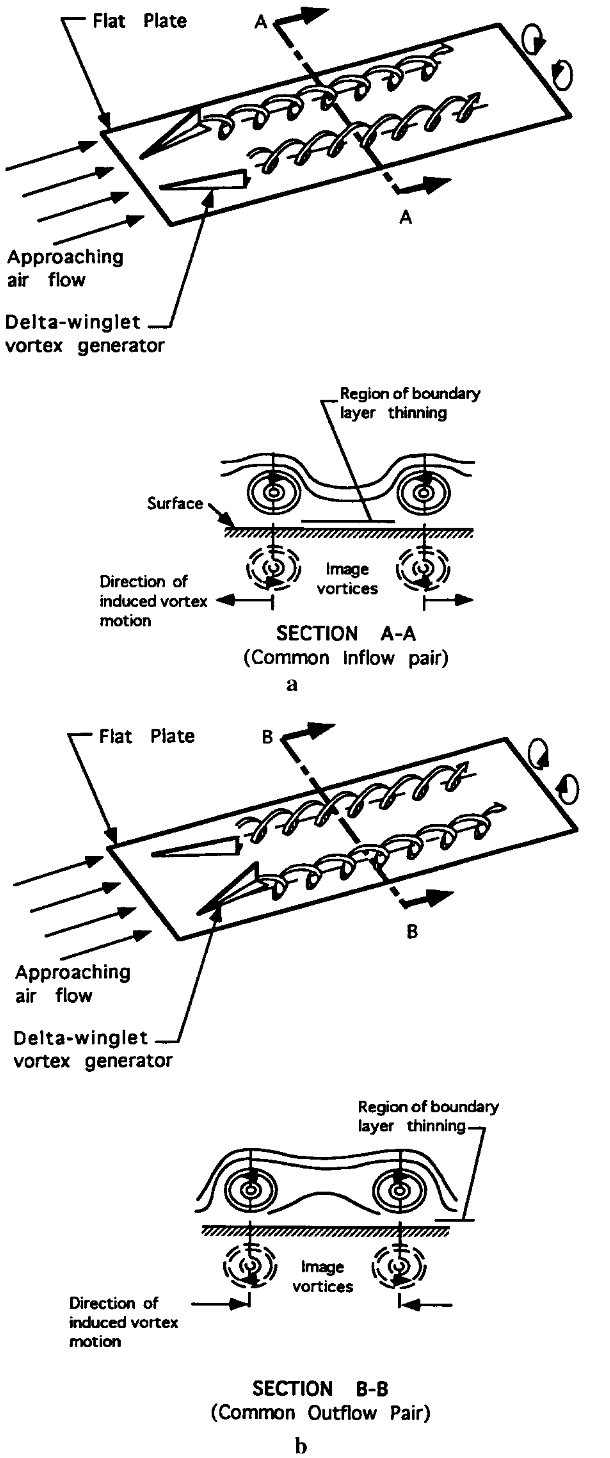

Figure 2. A schematic representation showing two vortex pairs. (*a*) A common inflow pair; (*b*) a common outflow pair. Regions of boundary layer thinning that are responsible for local heat transfer enhancement are indicated. The imaginary reflection (image) vortices are also shown, and the induced velocities of the vortices are indicated.

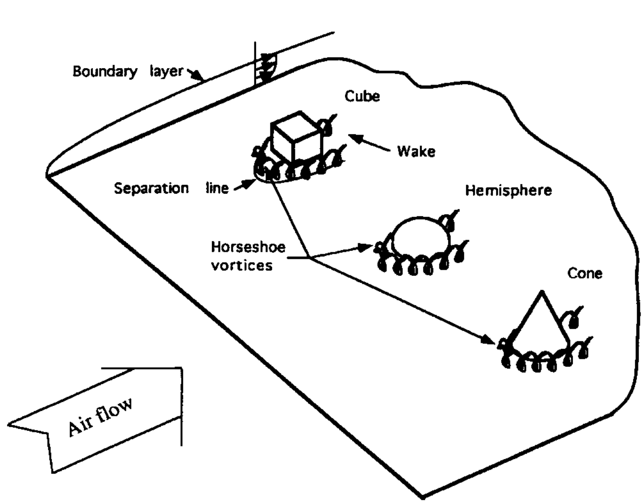

Figure 3. Several surface protuberances are shown: cubes, hemispheres, and cones. The locally intense horseshoe vortices due to these boundary layer protrusions are also shown in the figure. The legs of a horseshoe vortex represent longitudinal vortices.

berance; however, the location and height of the protuberance are important. The disturbance height must be comparable to the local displacement boundary layer thickness. Longitudinal vortices caused by surface protuberances were found to persist for more than 100 disturbance heights downstream. These horsehoe vortices are similar to those formed at the junction of a cylinder and flat plate (see Fig. 1*a*). The legs of a horseshoe vortex system form a pair of counterrotating streamwise vortices. The flow and heat transfer associated with junction vortex systems have been studied in detail [6–13], but the focus has been on the separation region near the junction and not on the downstream effects of the longitudinal vortices.

The interaction between a longitudinal vortex and a turbulent boundary layer has received some attention. Shakaba et al. [14] experimentally studied the behavior of a single longitudinal vortex embedded in a developing turbulent boundary layer with a zero pressure gradient. Their measurements indicated that the streamwise vorticity was very persistent, being reduced only by the spanwise surface shear stress. Furthermore, they found that the structure of the boundary layer turbulence was modified such that simple algebraic eddy viscosity models would not give accurate detailed results.

Eibeck and Eaton [15] conducted detailed heat transfer measurements for a single longitudinal vortex embedded in a turbulent boundary layer. Interaction of the vortex with the wall caused the vortex to be skewed but stationary in the flow. This skewing can be explained using a potential flow model and considering Fig. 2. A single longitudinal vortex interacts with the wall as if it were interacting with a mirror image of itself reflected in the wall. In other words, by symmetrically reflecting the potential flow about the wall, the interaction of the flow with the wall can be visualized as the interaction of the flow with its image (this is called the "method of images"). The vortex and its image mutually induce a spanwise velocity

as shown in Fig. 2.[1] The effective time for spanwise convection of the vortex and its image increases in the streamwise direction and causes the vortex to be skewed with respect to the streamwise flow. The heat transfer measurements of Eibeck and Eaton indicated a peak enhancement of about 25% in the region of inflow (downwash region or flow toward the wall) and a heat transfer decrease of as much as 15% in the outflow (upwash) region—these effects persisted through the entire test section, which was about 100 boundary layer thicknesses long. Eibeck and Eaton interpreted their results as indicating that the local heat transfer effects were due to mean flow changes and not to changes in the turbulence structure. Through a simplified calculation comparing measured enhancements to predictions from a correlation based on the Reynolds analogy, they used their data to support the validity of an analogy between skin friction coefficient and the Stanton number.

Multiple longitudinal vortices embedded in a developing turbulent boundary layer were experimentally studied by Mehta and Bradshaw [16]. In this extension to their earlier work [14], they considered a vortex pair rotating such that the fluid between the vortices flowed away from the wall. In this outflow configuration, the vortices tended to move away from the plate and persist through the entire test section. Significant structural changes in the turbulence were observed, and they felt that algebraic turbulence models were not sufficient for such flows. To buttress this conclusion, they cited failed attempts to capture the essential flow features of an embedded longitudinal vortex using mixing length, k–ϵ, and stress transport models. Pauley and Eaton [17] conducted mean flow measurements with vortex pairs in a turbulent boundary layer, but they studied both common inflow and outflow configurations. The interaction of a common inflow pair with the wall resulted in a widening region of boundary layer thinning between the neighboring vortices, and the common outflow pair behaved as reported by Mehta and Bradshaw.

These observations may be explained by considering the induced velocities of the vortices and their images. For a common inflow pair, the vortices will induce each other toward the wall. Upon approaching the surface, the vortex will eventually interact more strongly with the wall than with the other vortex (as if it's interacting with its image). Interaction with the wall, envisioned using the method of images, results in one vortex moving away from the other. A common outflow pair behaves conversely. If the vortices of a common outflow pair are close enough to interact, they induce each other away from the wall. If they are far apart and interact more strongly with the wall, they will be induced toward each other to eventually lift away from the surface.

Shizawa and Eaton [18] studied a single vortex in a pressure-driven three-dimensional turbulent boundary layer. Their experimental measurements indicated that the sign of the vorticity was important in its interaction with the boundary layer. If the vortex induced a flow near the wall in the same direction as the transverse velocity of the boundary layer, then vortex-induced perturbations in the boundary layer decayed quickly. If the vortex induced a velocity near the wall that opposed the transverse flow in the boundary layer, then a strong transverse separation occurred, and boundary layer perturbations persisted. The flow for these two cases is shown schematically in Fig. 4. Conventional turbulence models were expected to fail at predicting the Reynolds stress field, due to large structural changes in the turbulence. However, the degree to which turbulence complexities would affect mean flow predictions was unclear.

Zhang and Collins [19] computationally studied a single longitudinal vortex generated by a circular jet that issued through the wall into the turbulent boundary layer. Their numerical code, which solved the averaged Navier–Stokes equations using a conventional k–ϵ model, was validated by comparing the calculated circulation to a wind tunnel measurement. The calculated and measured circulation differed by 11% for that case, but no comparisons of calculated and measured vorticity or velocity distributions were given. Their results showed that a vortex positioned in the outer region of the boundary layer enhanced heat transfer and persisted. A vortex produced well inside the boundary layer was weaker, decayed quickly, and could adversely affect heat transfer. For fixed pitch and skew angles, the ratio of jet velocity to free-stream velocity determined the location of the longitudinal vortices within the boundary layer. In view of the studies discussed earlier [14–18], the justification of a conventional k–ϵ model for this flow is weak; while the results are intuitively satisfying, they may not be correct in their detailed quantitative predictions.

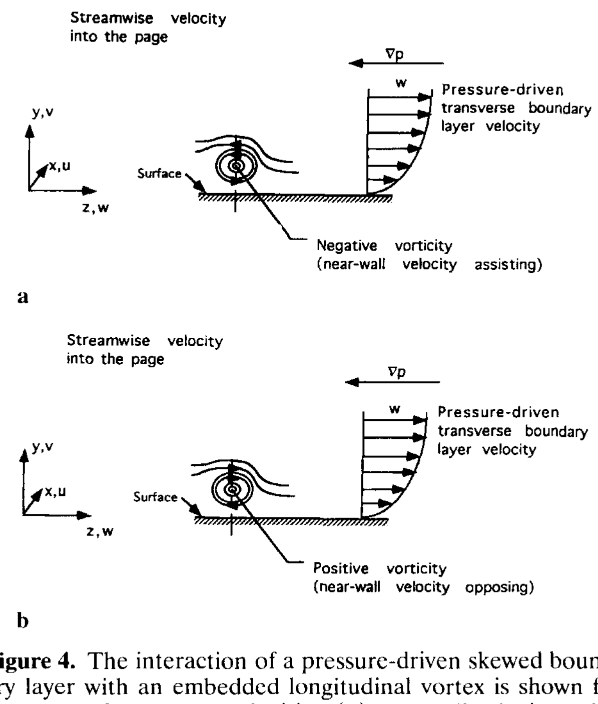

Figure 4. The interaction of a pressure-driven skewed boundary layer with an embedded longitudinal vortex is shown for two cases of transverse velocities: (*a*) near-wall velocity assisting, (*b*) near-wall velocity opposing.

[1] This induced velocity may be visualized by first imagining that you are sitting on the core of one vortex watching the other as it is carried in your velocity field. Then change your perspective so that you are sitting on the opposite vortex with its velocity field. These two observations, taken together, allow you to infer the induced advection of the vortex pair (the vortex and its image). A smoke ring provides a related example; the curved vortex has a self-induced advective velocity.

The similarity between momentum, heat, and mass transfer for a temporally developing Goertler vortex flow was considered by Liu and Sabry [20]. They pointed out that this flow with streamwise vorticity, shown schematically in Fig. 5, is very similar to those obtained with vortex generators (a Goertler vortex system forms naturally in the boundary layer on a curved surface). For unity Prandtl and Schmidt numbers, the unsteady and spatially developing problems have a simple boundary layer analogy: velocity is directly analogous to temperature and concentration. Applying this analogy and using velocity data Liu and Sabry conclude that the advective velocities normal to the plate are responsible for the heat transfer enhancements observed with longitudinal vortices. Furthermore, they suggest that future experiments should exploit the analogy. The Goertler vortex flow is spanwise periodic; the authors did not directly address the implications of the nonperiodic spanwise conditions common in application.

In this section, we have discussed the early development of vortex-induced heat transfer enhancements and the more recent fundamental studies that help to understand the physical mechanisms important to the flow and heat transfer. It is possible to actively or passively produce a single vortex or co- or counterrotating vortex pairs alone or in various combinations with each other by appropriately selecting and placing the vortex generators. These vortices will interact with each other and with those naturally occurring in the flow. In the next section, the use of passively generated longitudinal vortices is discussed in detail, with a focus on heat exchanger applications.

PASSIVE VORTEX METHODS

Early Applications

The use of longitudinal vortices to enhance heat transfer on flat surfaces was studied in the mid-1970s by Edwards and Alker [21]. They presented experimental results from a study in which cubes and delta winglet vortex generators of a design following Johnson and Joubert [3] were placed in a fully developed duct flow. They addressed the effects of size and spacing of the cubes and generators, and they collected data with co- and counterrotating vortex pairs.

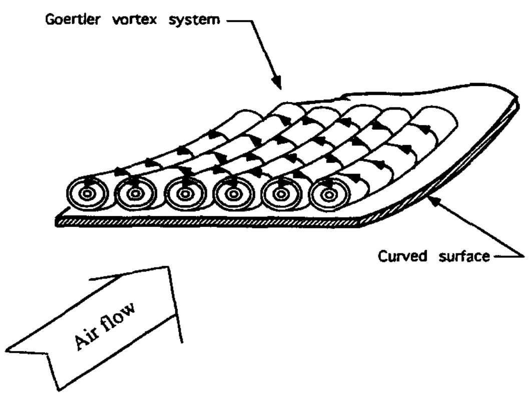

Figure 5. A Goertler vortex system represents another natural vortex flow that occurs in a boundary layer on a curved surface. Except for the spanwise periodicity exhibited by this flow, it is very similar to the passively generated vortex flows under consideration; the vortices are longitudinally oriented.

The results, discussed in terms of longitudinal vortices and separation and wakes, indicated that cubes provided a greater enhancement than delta winglet vortex generators (see Fig. 1*c*), with a maximum local Nusselt number enhancement of about 76%. In keeping with the more fundamental studies of boundary layer effects discussed in the previous section, counterrotating vortices were found to perform better than corotating vortices. No pressure drop data were provided.

In 1982, Russell et al. [22] apparently reported the first use of longitudinal vortices to enhance finned tube heat exchanger performance. They conducted experiments using a transient melt line method to assess the effectiveness of several vortex generator configurations and, after considering delta and rectangular winglets, found a rectangular winglet in two staggered rows to be most promising. They implemented this geometry in a full-scale finned flat-tube heat exchanger with the winglets at 20° angles of attack and the holes (due to punching the winglet) downstream of the winglet. Measured data were compared to "typical" plain-tube correlations, and at a Reynolds number of 500 the j factor was enhanced by about 47% while the f factor increased by 30%. At a Reynolds number of 1000, the results were more encouraging, with a j factor increase of about 50% and an f factor increase of only 20%. The authors concluded that vortex enhancement offered significant promise, providing a ratio of j/f that exceeded 0.5 for Reynolds numbers between about 1500 and 2200. The greatest weakness of this study was that full-scale tests with an unenhanced but otherwise identical heat exchanger were not conducted; the authors relied on "typical" correlations from the literature, and it is common for such correlations to deviate by 10–30% in predictions of j and f factors.

These early studies cultivated interest in the topic, and in 1986 two more papers appeared. Turk and Junkhan [23] presented experiments with rectangular wing vortex generators of various heights and angles of attack placed near the leading edge of a heated flat plate. They considered flow with a zero or favorable pressure gradient. Local spanwise-average heat transfer was enhanced by nearly 200% in some cases. In general, the enhancement increased with a favorable pressure gradient. Fiebig et al. [24] studied vortex generators in the form of one delta wing and one delta winglet pair in a rectangular channel with Reynolds numbers between 1360 and 2270. Using the unsteady liquid crystal thermography method, they also reported local enhancements of up to 200%. The delta wing provided the highest local enhancement. Overall Colburn j factors were increased by 20–60% at Re = 1360.

Mixed and Forced Convection in Rectangular Channels

In the last five years, there has been considerable interest in the passive generation of longitudinal vortices for enhanced heat transfer performance. Several publications per year have appeared on the topic, with Fiebig and coworkers [25–41] being especially assiduous in their research on the application of passive vortex-induced enhancement methods. All of their published experimental results have been based on unsteady liquid crystal thermography for local heat transfer measurements. The pressure drop performance has been studied from drag force

measurements [24, 30–34] or pressure measurements [38–40]. The unsteady liquid crystal method essentially consists of suddenly exposing an isothermal specimen to an air flow with a different temperature and monitoring the temperature distribution on the specimen's surface with thermographic liquid crystals during the heating (or cooling) process. The heat transfer coefficient is inferred from the temperature history of the specimen. The experimental uncertainty depends on the particular implementation and test conditions. In general, the method is subject to concerns about whether the thermal conditions of the test reflect realistic heat exchanger conditions and whether conduction within the fin affects the inferred flux; furthermore, it may be difficult to determine and properly account for changes in the reference temperature (local bulk average or mixing cup temperature of the flowing air). Drag force measurements were obtained by suspending the test heat exchanger in a vertical test section and measuring the change in weight attributed to the flow. Again, the uncertainties due to this method depend on the implementation and test conditions; one should keep in mind that the method neglects changes in momentum flux from the inlet to the exit (only frictional and pressure effects are considered, and the importance of inertial effects for some cases remains unclear). The experimental uncertainty in the heat transfer coefficient is 2.6–6.3%, and the uncertainty in the drag measurement is 6.5% [32].

For these flows, there are several important length scales and geometrical effects. The original reference should be consulted for a detailed description of the geometry. However, two important points should be kept in mind. First, gravity was orthogonal to the fin surface in all the mixed convection studies, and the channel height was the relevant length scale. Second, in evaluating the enhancement it is useful to consider the ratio of the area of the vortex generator to the enhanced fin area. For the cases reviewed, the vortex generator area was less than a few percent of the fin area.

A numerical study of developing laminar mixed convection in a rectangular channel with wing-type vortex generators [25] demonstrated that the passive generation of longitudinal vortices can be used to enhance natural secondary flows (in this case buoyancy-driven). Calculations were performed at Reynolds numbers of 500 and 1815 with Grashof numbers of 0, 2.5×10^5, and 5×10^5. A single delta wing, with a unity aspect ratio[2] and attack angles of 20° and 26°, was attached along its trailing edge to the bottom of the channel. In this simulation, the channel wall did not have a hole under the wing, and since wings are usually formed by punching them from the fin, this geometry may not be realistic. With no hole under the wing, the formation of a horseshoe vortex system in addition to tip vortices is expected because the boundary layer must separate upstream of the wing; however, these calculations do not reflect that behavior. This numerical model was later extended by Biswas and Chattopadhyay [42] to include the hole under the delta wing for forced convection heat transfer. A comparison of the results is complicated by a large number of design parameters (channel dimensions, wing dimensions, angle of attack, placement, etc.). Nevertheless, for a long channel at Re = 500, with a wing at an attack angle of 26° having no hole beneath it, the average Nusselt number increased by 34% while the friction factor increased 79% over the plain channel geometry. For otherwise identical conditions with a hole beneath the wing, the average Nusselt number increased by 10% and the friction factor increased by 48% over the plain channel geometry. The calculated local Nusselt numbers (with a hole under the wing) were compared to independent experiments, and the numerical results were found to overpredict by about 10% the Nusselt number immediately downstream of the wing and to underpredict by about 10% Nu at distances greater than about one chord length downstream of the wing.

A very similar numerical study [26] was conducted to model a developing forced convection laminar flow between parallel flat plates with delta wings and delta winglet pairs. This study included a hole due to punching of the delta wings and winglets from the plate. For a delta wing with an aspect ratio of unity and an angle of attack between 10° and 50°, simulations were conducted for $500 < \mathrm{Re} < 2000$. The simulations predicted that the vortices induced transverse velocities on the order of the streamwise velocity. Interaction of the vortices with the wall, in particular bending from the plane of the delta wing to the plane of the wall where the wing is attached to the wall, distorted the vortex cross section from a circular to an ellipitical shape. Interaction with the wall also produced vortex spreading for common inflow vortex pairs in keeping with the earlier discussion of induced motion (and the method of images). Vortex spreading produces a growing region of boundary layer thinning and enhanced heat transfer. Presumably, this effect will continue until vortex breakdown, or until the vortices have moved so far apart that they no longer interact (it is presently unclear how far apart is "far apart"). Overall heat transfer enhancements of 84% were predicted for a delta winglet pair with an angle of attack of 30° and Re = 4000. This study included some flow visualization results. No pressure drop data were presented, and there was no quantitative comparison to experiments. Another minor extension to this work [27] indicated that when vortices are generated within a channel, there is an axial velocity defect in the core, and the vortices remain stable at angles of attack exceeding 50°.

Zhu et al. [28] presented numerical simulations of a vortex pair embedded in a turbulent boundary layer. Their approach included a conventional k–ϵ model for turbulence closure. They compared their predictions to experimental results [17] and found that velocity magnitudes were predicted to within 13%. However, the computational domain began 8.8 chord lengths downstream of the delta winglet vortex generator, and no indication was available as to whether flow near the delta winglet was well predicted. Vorticity distributions and decay appeared to be poorly predicted, but no quantitative comparison was presented. In an extension to this work, the authors presented simulations of a delta wing, a rectangular wing, a delta winglet pair, and a rectangular winglet pair in a developing turbulent channel flow [29]. The computational results predicted overall heat transfer enhancements of

[2] A common definition of the aspect ratio of a wing is $\Lambda = (\mathrm{span})^2/(\mathrm{planform\ area})$; however, the definitions given in Fig. 1c have been adopted to make this article consistent with the related literature.

16–19% with a 300–400% increase in flow loss.[3] They concluded that heat transfer augmentation in turbulent channel flows with longitudinal vortex generators is caused by an elevation of the turbulent kinetic energy level near the wall and an exchange of fluid in the near wall and core regions of the channel. These numerical simulations also used a k–ϵ turbulence model. No comparison to experiments was offered. From these studies, it is apparent that a longitudinal vortex in the center of a turbulent channel flow has little enhancement effect; the location of the vortex depends on the generator size and geometry, and it is more useful to generate a vortex near the wall so that it disturbs the laminar sublayer.

Fiebig et al. [30] reported experimental results for a channel flow with longitudinal vortex generators, extending their earlier work [24]. Measurements of the heat transfer coefficient were obtained using the transient liquid crystal method for Reynolds numbers between 1000 and 2000. Delta and rectangular wings (attached by their trailing edge) and winglets (attached along their chord) with aspect ratios between 0.8 and 2 and angles of attack between 10° and 60° were tested. The configurations were limited to a single delta or rectangular wing, a single delta or rectangular winglet, or a single pair of delta or rectangular winglets. The enhancement evaluation, based only on the area downstream of the vortex generator, showed that the heat transfer increases by up to 50%, and the pressure drop increases by approximately 45%.[4] Generator geometry effects were presented, and delta wings were found to be the most effective per area of the vortex generator. The results from this study are summarized in Fig. 6.

Using the same methods, this work was extended to consider two aligned rows of delta winglet pairs [31]. Tiggelbeck et al. found that the qualitative flow structure, the number of developing vortices per vortex generator, and their streamwise development were independent of the nature (uniform or vortical) of the flow approaching the vortex generator. Vortices generated by the second row were, however, found to be less stable than those generated by the first row. Nevertheless, the local heat transfer enhancement behind the second row of vortex generators was higher than that behind the first row. Local enhancements of several hundred percent were measured at Re = 5600, and overall heat transfer increased 77% for two pairs of generators. No pressure drop data were provided; furthermore, while the test method ostensibly models a perfect fin, the fin efficiency in application may be affected by the highly nonuniform local heat transfer due to conjugate convection and fin conduction, but these effects were not considered. This work was further extended by Tiggelbeck et al. [32]; they considered the previous geometry, except that in addition to two pairs

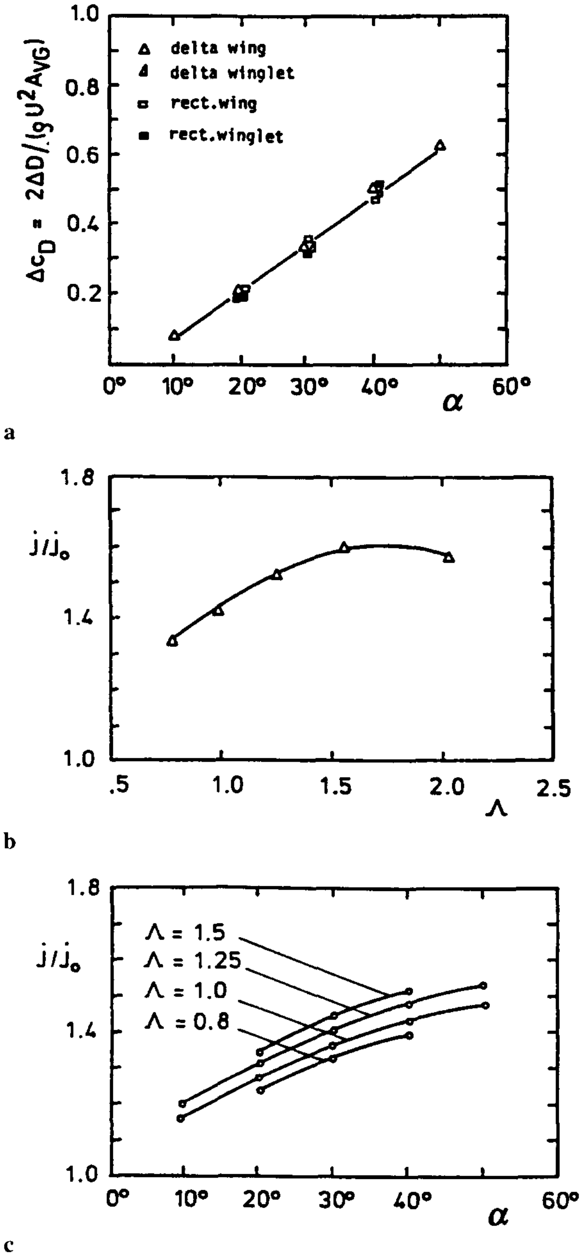

Figure 6. Results from heat transfer and drag measurements obtained by Fiebig et al. [30] (*a*) Induced drag coefficient of vortex generators in a developing channel flow as a function of angle of attack for various generator shapes at 1360 < Re < 2270. (*b*) Heat transfer enhancement as a function of aspect ratio for a single delta wing of constant area at a 30° angle of attack for Re = 1815. (*c*) Heat transfer enhancement as a function of angle of attack for wings of fixed span but differing aspect ratios, for Re = 1815. The zero subscript indicates performance without vortex generators. (Taken from [30].)

[3] Flow loss refers to the dimensionless dissipation number, ϕ, which is an apparent friction factor corrected for changes in the distribution of kinetic energy. See [29] for details.

[4] In these experiments the pressure drop was very low, so the authors measured changes in drag force on a specimen suspended within the wind tunnel test section. They cite a related numerical study that demonstrates for a particular channel flow that pressure and velocity nonuniformities contribute less than 6% to the total pressure drop. Based upon this result, they suggest that drag measurements are directly analogous to pressure drop measurements.

of vortices with common inflow (aligned rows), an upstream pair with common inflow and a downstream pair with common outflow (staggered) were included (see Fig. 7). At Re = 4600, they found that the aligned geometry showed a 60% increase in heat transfer and an increase in pressure drop of approximately 145%. The staggered geometry provided a heat transfer increase of 52% and an increase in pressure drop of approximately 129%. The higher performance of the aligned geometry may be due to the tendency for a common inflow pair to remain close to the surface, while a common outflow pair tends to move away from the surface (see the earlier discussion of induced vortex motion and the method of images). Again, there was no attempt to account for conjugate conduction and convection (fin efficiency) effects.

Channels with Single Tubes in Cross Flow

There have been a number of recent studies directed toward enhanced heat transfer in a channel with a single tube [33,34] using a single delta winglet pair located symmetrically upstream or downstream of the tube as shown in Fig. 8. At a Reynolds number of 5000, overall heat transfer can be increased by about 20% and pressure drop decreased about 10% for this simplified geometry. These results, summarized in Fig. 9, were obtained using the transient liquid crystal thermography method, which ostensibly models a constant temperature boundary condition. Due to its finite thermal conductivity, a real fin will not be isothermal in application. Therefore, a real fin will have a fin efficiency less than 100%. Conjugate convection and conduction was considered in a related computational study by Fiebig and Sanchez [35]. They considered a single pair of delta winglet vortex generators symmetrically located downstream of the tube. These delta winglets had an aspect ratio of 0.75 and an angle of attack of 45°. The numerical simulations of laminar incompressible flow indicated that these vortex generators operating at Re = 1200 could achieve the same heat duty as a heat exchanger without vortices at Re = 2000. At Re = 2000, the fin thickness could be reduced by 50% if vortices were used, or pumping power could be reduced 80% at a constant duty, or heat duty could be increased 25% at constant pumping power. The numerical results predict that the vortex-induced variations in local heat transfer coefficient cause the fin efficiency to deviate by more than 10% from the case with no vortex generators. Fiebig and Sanchez [35] also point out that spanwise variations in bulk (mixing cup) temperature can result in the prediction of negative Nusselt numbers when the heat transfer coefficient is

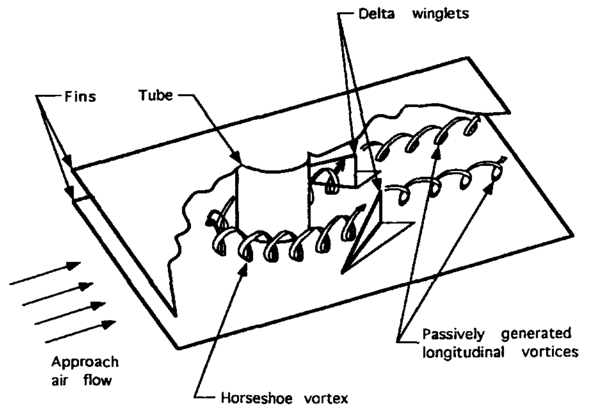

Figure 8. The arrangement of fin, tube, and delta winglet vortex generators studied by Valencia et al. [37]. They suggest that placing winglets symmetrically downstream of the tube as shown is the optimal location for the generators with respect to the tube.

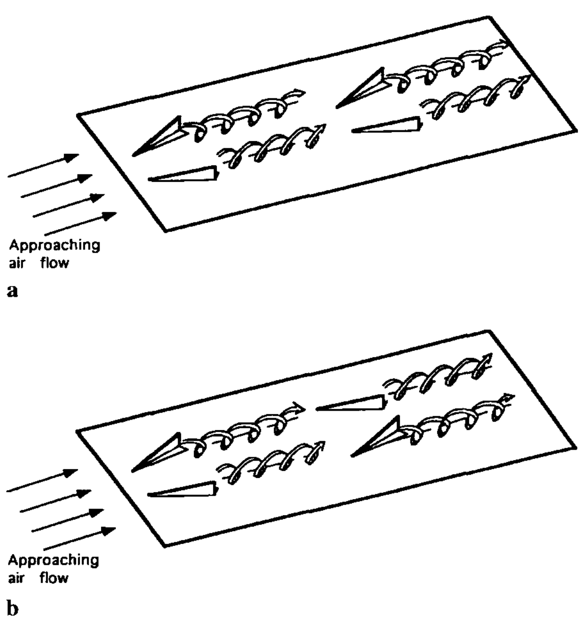

Figure 7. Two delta winglet pairs producing counterrotating longitudinal vortices in (*a*) an aligned configuration (common inflow/inflow) and (*b*) a staggered configuration (common inflow/outflow).

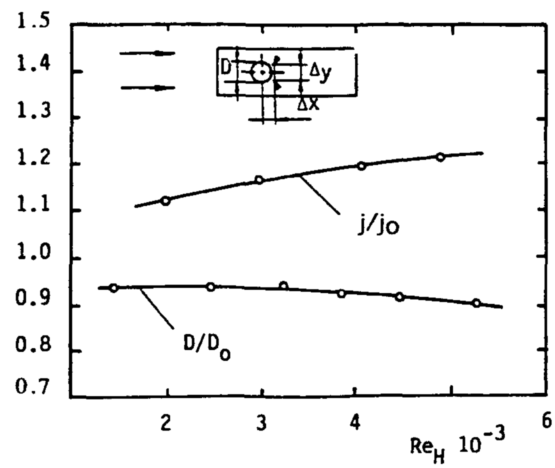

Figure 9. Heat transfer enhancement and drag reduction is a function of Reynolds number for a "near optimum" winglet position, $\Delta x/D = 0.6$ and $\Delta y/D = 0.8$, at a 45° angle of attack. The zero subscript indicates performance without vortex generators. (Taken from [33].)

based on spanwise-averaged bulk temperatures. They recommend the use of a dimensionless heat flux to avoid this situation but note that local reversals in heat transfer occur unless the wake region is enhanced. This local heat transfer reversal was the motivation for placement of their vortex generators near the tube wake. No comparison of the numerical simulation to experimental data with vortex generators was provided. However, a recent numerical study allowed such a comparison to experiments. Biswas et al. [36] compared their numerical computations for a single pair of delta winglet vortex generators symmetrically located downstream of a single tube at Re = 646 to experimental data for identical geometrical conditions, but they did not account for conjugate effects. (In the original paper, this Re was erroneously given as 500 [37].) While comparisons of overall results were generally good, there were relatively high discrepancies in local behavior near the winglet and immediately downstream. They thought that this was due to the simulated vortex strength being higher than that of the experiments.

Channels with Multiple Tubes

The use of passive vortex enhancement in a geometry with multiple tubes has been experimentally studied for a heat exchanger unit consisting of several fins and three tube rows of inline or staggered round tubes (see Fig. 10) [38, 39]. As shown in Fig. 10, using a pair of delta winglet vortex generators downstream of each tube was found to increase heat transfer by 55–65% for inline tube arrangements and by 9% for staggered tube arrangements. For inline tube arrangements, vortices increased the friction factor by 20% at Re = 600 and 44% at Re = 2600. The increase in friction factor for staggered tube arrangements was very small, ~ 3%. Another report extended this work to explore the behavior of flat tubes as compared to round tubes [40]. Measurements were conducted for 600 < Re < 3000, and the overall heat transfer enhancement for a flat-tube heat exchanger with delta winglet vortex generators was about 100%, with a pressure drop increase also of about 100%. The experiments were conducted with the flat tube located at the leading edge of the fin (due to a construction requirement [37]), but the round tube was substantially downstream from the leading edge. In this case, a strong horseshoe vortex forms naturally near the round tube, but none can form on the first row of flat tubes (since no boundary layer has developed). Longitudinal vortices influence the areas between the flat tubes, and applying a secondary flow enhancement to these two different cases will inherently favor the flat tube. This is true because in the round tube case a vortex is being added to a flow that already has a strong secondary flow (the horseshoe vortex), but in the flat tube case a vortex is being added to a flow that did not have a strong secondary flow; the impact is almost certain to be greater in the latter case. In other words, the unenhanced flat tube configuration was artificially inferior due to the placement of the tubes. Vortex enhancement would be expected to have a significant impact for this case, but comparisons to the round tube enhancements are difficult to evaluate. Nevertheless, the enhanced flat tube geometry offers more than twice the heat duty and half the pressure drop compared to the round tube geometry with identical vortex generators.

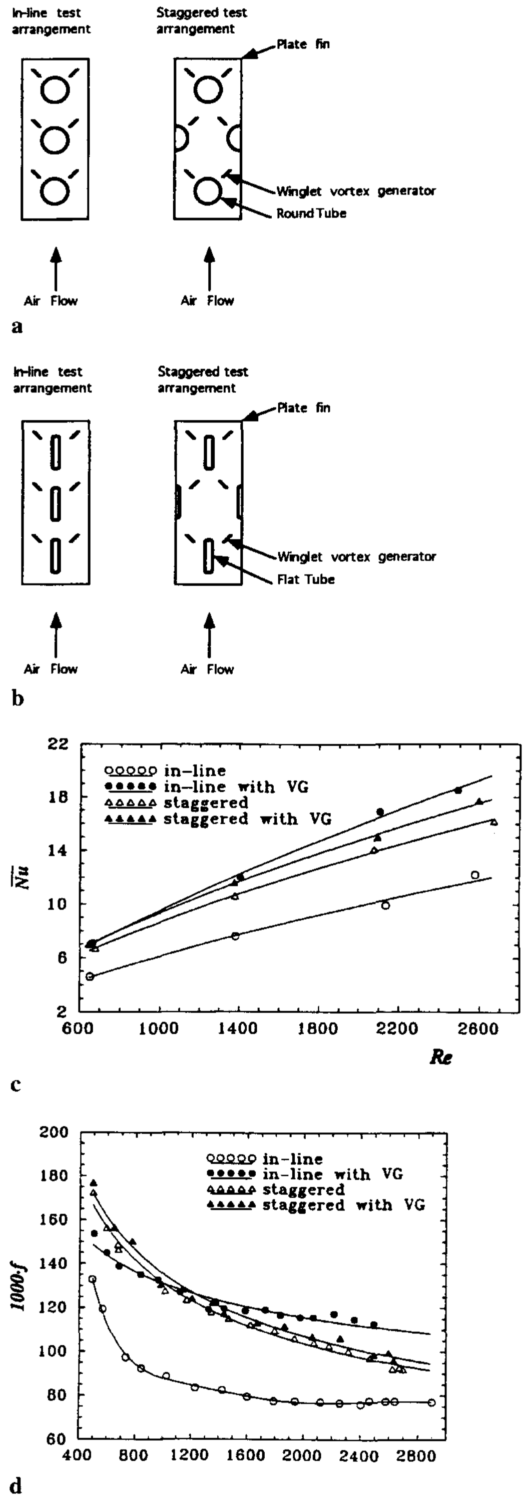

Figure 10. Heat transfer and pressure drop results for vortex generators with inline or staggered tube arrangements. (*a*) The round-tube geometry; (*b*) the flat-tube geometry; (*c*) area-averaged Nusselt number; (*d*) friction factor for a channel with three tube rows. The geometries of the fin, tube, and vortex generators were otherwise fixed. Figures (*c*) and (*d*) are taken from Fiebig et al. [39].

Summary of Literature on Passive Vortex Methods

The extant literature on passive vortex-induced air-side heat transfer enhancement has been reviewed by topic: early applications, mixed and forced convection in rectangular channels, channels with single tubes, and channels with multiple tubes. The number and range of the design parameters that have been reported in the literature is extensive.[5] An abbreviated summary of the results is presented in Table 1.

Although the summary given in Table 1 is necessarily simplified, with the details left to the cited reports, the following conclusions are supported. To date only two classes of wing geometry have been studied in any detail as vortex generators: delta-shaped wings and winglets, and rectangle-shaped wings and winglets. In general, the delta wing and winglet offer heat transfer and pressure drop performance superior to that of the rectangular geometry, but the rectangular winglet is competitive in some cases. The pressure drop penalty incurred during application to turbulent channel flows apparently makes the method unattractive for such flows. The use of delta winglets downstream of a tube or with flat-tube heat exchangers under laminar flow conditions is the most successful arrangement examined for application. Unfortunately, experiments and simulations have focused on Reynolds numbers that are substantially higher than in many common applications, with most of the studies conducted for Re > 1000 and the effectiveness at Re < 500 still uncertain due to measurement difficulties; for Re = 400, computational results indicate approximately a 20% increase in Nu and an 40% increase in drag coefficient for a fin-tube exchanger with delta winglets [35].

[5] A complementary review, restricted to vortex methods for compact heat exchangers, is currently in press [41].

ACTIVE VORTEX METHODS

As in other active heat transfer enhancement methods, the advantages of active secondary flow methods are associated with control. Under certain conditions, it may be desirable to increase heat transfer rates to meet duty requirements even at the expense of increased pumping power. However, there may be other conditions where the heating or cooling demand could be met with lower pumping power. Active vortex generation affords control over the heat transfer and pressure drop behavior. When there is a demand for heat transfer performance, vortices are introduced, along with the expense of the power to produce them and the added pressure drop. When demand drops, vortex generation ceases and so do the parasitic pressure drop and power requirements.

There are a number of ways to achieve this control; however, there has been very little work directed at active vortex methods, and to our knowledge there has been no study of active vortex generation in a heat exchanger application. The lack of attention is probably due to the increased capital and operating costs and potential operating problems associated with an active approach and the uncertain benefits of an enhancement method that is

Table 1. A Summary of Passive Vortex Enhancement Results

Ref.	*Geometry*	*Re / (10³)*	*Overall Heat Transfer[a] Enhancement*	*Pressure Drop Penalty*	*Method of the Study*
21	Cubic protuberances and delta winglets	61	76% cube 42% counter 15% corot (local)	Unknown	Luminescent phosphor
22	Plate-fin heat exchanger (full scale)	0.3–2.2	50%	20–30%	LCT[b]
23	Flat plate/rectangular winglets	30–300	100%	Unknown	Conventional thermocouples
24	Rectangular channel with a delta wing, delta winglets, and rectangular winglets	1.36–2.27	20–60% (delta wing)	Unknown	LCT
25, 42	Rect. channel with delta wing (no hole)	0.50	34%	79%	Computational
	Rect. channel with delta wing (hole)		10%	48%	
26, 27	Parallel plates with a delta winglet pair	1.0–4.0	84%	Unknown	Computational
28, 29	Turbulent boundary layer/channel wall	50	16–19%	300–400%	Computational
30–32	Rectangular channel				
	delta wings	1.0–2.0	50%	45%	LCT and drag measurements
	winglet pair	5.6	77%	Unknown	
	multiple pairs, inline	4.6	60%	145%	
	multiple pairs, staggered	4.6	52%	129%	
33–36	Rectangular channel with one tube, winglet pair downstream of tube	5.0	20%	−10% (lower ΔP)	LCT/drag [33, 34]; computational [35, 36]
38, 39	Three tube rows				
	inline round	0.6–3.0	55–65%	20–44%	LCT and drag
	staggered round		9%	3%	
	flat tubes		100%	100%	

[a] Typical or maximum overall heat transfer enhancement unless otherwise noted.
[b] Transient liquid crystal thermography.

not very well understood. We will very briefly discuss three possible ways to actively introduce a secondary flow in the form of a longitudinal vortex: skewed and pitched wall jets, electrohydrodynamics (EHD), and acoustic streaming.

When a jet issues from the heat transfer surface into the boundary layer, a longitudinal vortex may form as shown in Fig. 11. A numerical study of this flow was discussed earlier [19], and the method has been experimentally studied as a means of active boundary layer control [43, 44]. The jets are typically circular and are injected with particular pitch and skew angles with respect to the main flow (see Fig. 11). Studies of the effects of jet velocity, pitch, and skew [43, 44] indicate that the method requires injection velocities on the order of the free-stream velocity. Vortices can be generated for a wide range of jet skew; however, injecting a jet directly into the oncoming flow appears to be less effective. Numerical studies indicate that a jet injected with a pitch of 45° and zero skew (in the downstream direction) introduces two counterrotating vortices with common outflow. There has been at least one related computational study of the heat transfer due to such flows; Zhang [45] presented a computational study of heat and mass transfer due to jet-induced longitudinal vortices in a turbulent boundary layer. Turbulence was simulated with a k–ϵ model and a Reynolds stress model. Circular, ellipitcal, and square jets were simulated, and jet geometry was found to have little effect on heat transfer enhancement. Zhang cites several experiments that consider this method in gas turbine cooling; to our knowledge, there have been no studies directed at applying this technique to heat exchangers.

Electrohydrodynamics (EHD) is of current interest in heat transfer augmentation [46]. EHD relies on an externally provided electric field to produce an electric body force in the flow. This body force, which can be very localized and controlled, is used to produce a secondary flow known as a corona wind. For air flowing in an electrostatic field, the method is highly dependent on the charge density and electric field strength to produce a corona wind normal to the heat transfer surface. Most current EHD research is focused on generating and exploiting the corona wind directly (see [47] for an example); however, these normal velocities introduce streamwise vorticity and, as discussed above, the resulting secondary flow could take the form of a longitudinal vortex. Thus, EHD could be used for active vortex-induced heat transfer enhancement. Although EHD has not been explicitly directed at or coupled with vortex-induced enhancements, this coupling seems natural. There is currently no experimental evidence to support this approach or estimate its potential.

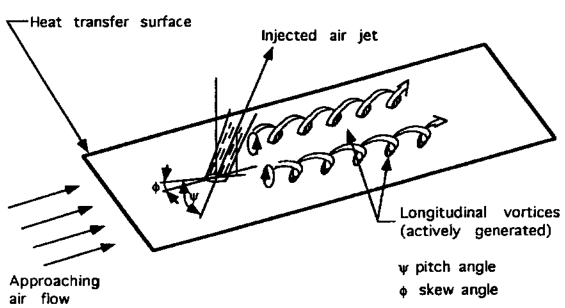

Figure 11. The use of an injected transverse jet to produce streamwise vortices for boundary layer control. Jet-induced vortices could be actively controlled.

A different way to actively generate a secondary flow is through acoustic excitation. Heat transfer enhancement by acoustic excitation has been studied for some time; an early review is provided by Lemlich [48], and more recent work has been reported [49–51]. The secondary flow may take the form of longitudinal vortices; however, its manifestation is highly dependent on geometry and flow conditions. We are unaware of any work in which acoustic excitation is used as an active method of vortex enhancement in a heat exchanger application, and we know of no experimental or theoretical work that will allow an assessment of its potential. Nevertheless, the coupling of acoustic excitation with vortex methods represents a possibility for active vortex-induced air-side heat transfer enhancement.

DISCUSSION

In heat exchanger design, laminar flow is often desired or necessary because of design constraints. However, it may be possible in some cases to "turbulate" the flow and thereby increase the heat transfer. An obvious question arises: for a prescribed duty, are there sound reasons to preferring a laminar main flow with a secondary flow enhancement over a turbulent main flow? An answer to this question can be developed from the following line of reasoning. A small heat transfer coefficient requires a large temperature difference for a given heat duty. A large friction factor requires a large pressure difference for a given flow rate. Large temperature differences and pressure drops are directly associated with higher entropy generation [52]. Our desire for high heat transfer coefficients and low friction factors reflects our preference for designs with low entropy generation. Entropy generation is directly related to heat exchanger performance. Furthermore, since entropy is associated with disorder, and a laminar flow is well ordered in comparison to a chaotic turbulent flow, the secondary enhancement method should be preferred over simple turbulation. Heat exchanger designs reflect this penchant, which may be extended to the following: Orderly laminar flow with streamwise vorticity will certainly have lower rates of entropy generation than the equivalent turbulent flow; therefore, vortex generation is preferred over turbulation. The argument has appeal; unfortunately, we are unaware of any systematic study comparing the local entropy generation due to flow and heat transfer for these two cases, nor are we aware of any second-law efficiency evaluation of vortex methods, and thus these appealing arguments are suppositional.

Numerous performance evaluation criteria have been suggested to compare the performance of heat exchanger surfaces [53, 54]; such comparisons can be very complex. Recently, Brockmeier et al. [55] used one of these criteria to explore potential heat exchanger surface area reductions by vortex enhancements. By prescribing a fixed heat duty and pumping power as design constraints, they compared the experimental performance of plate-fin exchangers with plain rectangular fins, triangular fins, offset strip fins, and louvered fins to the numerically predicted perfor-

mance of vortex generators, as shown in Fig. 12. The results indicated that the vortex-enhanced surface provided the best performance, requiring about 24% as much surface area as the plain rectangular fins. The offset-strip surface required 33% of the plain-fin area, and the louvered fins required 38% of the plain-fin area. These results suggest that the vortex generator surface is competitive with (indeed, superior to) the louvered and offset-strip surfaces. However, the louvered fin geometry selected from Kays and London [56] was from a previous-generation technology, and its performance is inferior to modern louvered fin exchangers. Because the comparison did not consider a modern louver geometry and because the vortex-enhanced performance was based on numerical studies for a simplified geometry (not experiments), it remains unclear whether or not vortex enhancement is truly superior to louvered designs.

CONCLUDING REMARKS AND RECOMMENDATIONS

Flow through heat exchanger passages is complex, and there are many important length scales and geometric features without the complication of vortex generators. Further research is needed to provide definite indications of how and when vortex-induced air-side heat transfer enhancement should be pursued in these complex channels. The current uncertainty is largely due to a lack of fundamental research. While the extant work has augmented our understanding, the emphasis has been on vorticity in a turbulent flat-plate boundary layer, and most compact heat exchangers operate with laminar developing flows. There have been numerical studies of laminar flows for simplified vortex generator geometries, but there has been very little analytical work to help generalize the numerical predictions. A deeper understanding of the flow and heat transfer interactions could identify the desirable features of vortex flows for heat exchanger geometries and point toward schemes for exploiting their full potential. Thus, further basic research should be directed at narrowing a complex design parameter space to the promising regions and generalizing the results for application to heat exchanger designs.

The extant experimental and numerical work directed at applying vortex-induced enhancements shows that the technique holds promise. Further experimental work in representative heat exchanger geometries may be helpful; however, it should be carefully limited to extending the geometrical and flow conditions that have been studied, to filling gaps in the currently available data, or to providing comparisons to model predictions. Careful experiments at low Reynolds numbers would be of particular value, as there have been few such studies published. Of more value would be to-scale experimental comparisons of vortex generator surfaces to current-generation competing surfaces in a compact heat exchanger. The viability of vortex-induced air-side enhancement must stand the test of a systematic study in an actual heat exchanger with and without vortex enhancement for flat fins (as in a tube-and-fin exchanger) or corrugated fins (as in a plate-fin exchanger). Such a heat exchanger will have more than three delta winglet pairs in the flow direction and more than three passages in the transverse direction, thus overcoming the end effects of all reported studies in the literature. The to-scale performance of vortex generators must be compared to alternative enhancements such as louvers and strip fins using an appropriate performance evaluation criterion. Finally, the effects of longitudinal vortices on heat exchanger fouling, water retention, or frost growth may need to be examined for some applications.

The use of longitudinal vortices as a secondary flow heat transfer enhancement method for heat exchanger applications shows promise, but its potential remains unclear more than a decade after its first application to a finned-tube geometry. A deeper understanding of the flow and heat transfer interactions is needed to identify promising implementations for specific applications. Full-scale experiments with heat exchangers and careful low Reynolds number experiments are needed to provide a level-playing-field comparison of vortex methods to competing enhancement techniques.

References 57–85 provide further discussions related to passive secondary flow enhancement.

We are indebted to anonymous reviewers for providing several references.

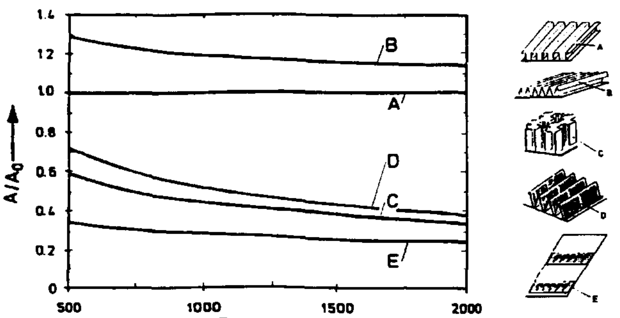

Figure 12. Total heat transfer area ratio as a function of the reference surface Reynolds number for fixed heat duty, pumping power, mass flow rate, and temperature difference. Surface A is the reference surface. (From Brockmeier et al. [55].)

NOMENCLATURE

A	area, m^2
b	wing span (see Fig. 1c), m
c	wing chord (see Fig. 1c), m
D	drag force on a test specimen, N
f	Fanning friction factor, dimensionless
H	plate spacing, m
h	heat transfer coefficient, W/(m^2 K)
j	Colburn j factor [$= \mathrm{Nu}/\mathrm{Re}\,\mathrm{Pr}^{1/3}$], dimensionless
k	thermal conductivity of air, W/(m K)
Nu	Nusselt number ($= hH/k$), dimensionless
p	pressure, Pa
Pr	Prandtl number, dimensionless
Re	Reynolds number ($= UH/\nu$), dimensionless
U	approach velocity, m/s

u, v, w streamwise, transverse, and spanwise velocity, respectively, m/s
x, y, z streamwise, transverse, and spanwise coordinate, respectively, m

Greek Symbols

α angle of attack for a wing or winglet (see Fig. 1c), deg
Δc_D change in drag coefficient (see Fig. 6), dimensionless
ΔD change in drag force, N
Λ aspect ratio for a wing or winglet (see Fig. 1c), dimensionless
ν kinematic viscosity of air, m^2/s
ρ air density, kg/m^3

Subscripts

0 reference (unenhanced) surface
VG vortex generator

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